Effects of non-linearities in a dual frequency Paul trap

SHORT SYNOPSIS

Submitted in partial fulfillment of the requirement of the degree of

DOCTOR OF PHILOSOPHY

to

Manav Rachna University

by

Anuranjan Kansal
Registration number: 2K20-PFE-007
Department of Electronics and Communication Engineering
Manav Rachna University, Faridabad

Under the supervision of

Dr. Charu Pathak (Supervisor)
Associate Professor
Department of Electronics and Communication Engineering
Manav Rachna University, Faridabad

Dr. Varun Saxena (Co-Supervisor)
Assistant Professor
School of Engineering
Jawaharlal Nehru University, New Delhi

MANAV RACHNA Vidyanatariksha

MANAV RACHNA UNIVERSITY
(FORMERLY MANAV RACHNA COLLEGE OF ENGINEERING
NAAC ACCREDITED 'A' GRADE INSTITUTION)
Declared as State Private University under section 2f of the UGC act, 1956

2019-2020

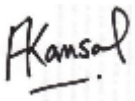
MANAV RACHNA
vidyanatarikshah

MANAV RACHNA UNIVERSITY
(FORMERLY MANAV RACHNA COLLEGE OF ENGINEERING
NAAC ACCREDITED 'A' GRADE INSTITUTION)
Declared as State Private University under section 2f of the UGC act, 1956

DECLARATION BY THE SCHOLAR

I hereby declare that the short synopsis "**Effects of non-linearities in a dual frequency Paul trap**" being submitted in partial fulfillment of the requirement for the degree of Doctor of Philosophy in Department of Electronics and Communication Engineering under Faculty of Engineering Manav Rachna University, Faridabad during the academic year 2019-2020.

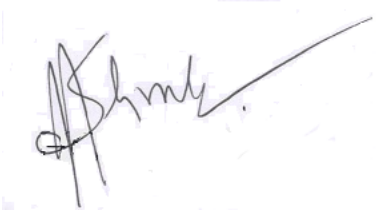
It is a bona-fide record of original work carried out under the supervision of Dr. Charu Pathak and Dr. Varun Saxena. It has not been submitted in full or part to any other university or institute for degree or diploma. Further, it is certified that short synopsis is within the plagiarism limit and copy of the same is attached as per University norms.



Anuranjan Kansal
Registration number:2K20-PFE-007

Dr. Charu Pathak (Supervisor)
Associate Professor
Department of Electronics and Communication Engineering
Manav Rachna University, Faridabad

Dr. Varun Saxena (Co-Supervisor)
Assistant Professor
School of Engineering
Jawaharlal Nehru University
New Delhi



Chairman, DRC

CONTENTS

S. No.	Description	Page No.
1	Identification of the topic of research	1
2	Statement of research problem	1
3	Abstract	1
4	Review of literature	1-4
5	Justification of the study	4
6	Objective of the study	4
7	Hypothesis	5
8	Research design	5
9	Research methodology	6
10	Scheme of chapterisation	6
11	Flow of work (academic year 2020-21)	6
12	Bibliography	7-10

1. Identification of the topic of research

Paul Traps are devices to trap sub-atomic particles in a small region for a long period of time. They find applications in the several areas of science such as mass spectrometry, atomic clocks, quantum computers, quantum information processing. Under ideal conditions, the dynamics of a charged particles is very well understood in a single frequency Paul trap, however, in a new newly conceptualized device, dual frequency Paul trap, the dynamics is not very well understood. Any real study must include elements of non-idealities. Hence, the attempt of this study is to analyse the dynamics in presence of certain non-linearities that are likely to exist inside a dual frequency Paul trap.

2. Statement of research problem

Effects of non-linearities in a dual frequency Paul trap.

3. Abstract

A analysis of dynamics of charged particles inside a dual frequency Paul trap in presence of non idealities is being studied. The trap may develop a phase mismatch between the electrodes where the RF voltage is applied. Moreover, an ideal trap assumes an ideal quadrupole potential. In reality, hexapole and octupole potentials develop inside the Paul trap. The non linear affects become dominant and modify the secular frequency inside the trap. In this study, we attempt to find the deviation in secular frequency that is likely to develop on account of hexapole and octupole fields.

4. Review of literature

The science of ion confinement evolved from molecular beam physics and spectroscopy. In 1953, W.Paul and H. Steinwedel introduced the concept of mass analysis of charged particles by trapping ions. They proposed the concept of what has been described by W. Paul in his Noble lecture in 1989 as quadruple mass filter [1, 2]. This mass filter comprised of four hyperbolically shaped electrodes. Periodically varying potentials were applied to electrode pairs which were placed along two given axis. Due to the periodically varying sign of the electric force developed between the pair of electrodes it was possible to achieve focussing and defocusing in both the direction where the electrode pairs were located alternating in time. Hence it was possible for the particles to traverse in the third direction longitudinally without hitting the electrodes. The concept of dynamic stabilization in two dimensions was extended to three dimensions to achieve what came to be known as an ion trap. This trap configuration comprises of a ring electrode, and two hyperbolic cap electrodes. The radio frequency electric field along with a DC field is applied to the electrodes.

Since its conceptualization, the ion trap was mostly used as a mass filter and underwent several stages of development. Soon after patenting the design in 1953 [3], W. Paul and H. Steinwedel introduced ways of detecting and measuring the ions while they were stored along with the contributions of H. Dehmelt. The period between 1953-1962 was termed as the first stage of mass selective detection in ion trap spectroscopy. The period between 1968-1976 witnessed a surge towards mass selective storage being pushed by scientists like R. E. March, P. H. Dawson, N. R. Whetten, J. F. J. Todd [4, 5]. This made it possible to produce a range of ion masses but operating the quadruple storage field in such a way so as to store only a single mass

ion in the trap. This single mass ion was then ejected for detection. The process was repeated rapidly until a complete mass spectrum was generated [6]. By 1980's came the stage of mass selective ejection guided by J. E. P. Syka, W. E. Reynolds, and P. E. Kelley, G. Stafford Jr. The trap could now hold ions over a large mass range simultaneously for a long duration of time. Surprisingly, the idea of using an altered form of mass filter for ion trapping was first introduced in 1989 [7]. This work was also quite significant in proving that even though both spherical and linear Paul traps were almost equivalent, mathematically, it was the linear Paul trap that was superior in context of higher ion capacity. However, in principle, it was actually the spherical Paul trap that could store more number of ions but experienced the problem of micro motion, a topic to be discussed later. Both the linear and spherical Paul trap could be used for trapping larger ion particles as well. However, the frequency of quadruple was quite small for the larger ion particles and therefore they experienced a large micro motion. Another quite significant development in the field of trapping was the development of the cooling mechanism [8]. It enabled researchers to reduce the motional energy of particles. Initially, without laser cooling technique, scattering was employed to cool particles were cooled by the use of buffer gas kept inside a vacuum chamber [9].

Interestingly, in 1979, the research group of W. Neuhauser, M. Hohenstatt, P. E. Toschek, H. Dehmelt, and P. E. Toschek was able to trap, cool and image a single barium ion [10]. This enabled the group to observe quantum jumps for the first time [11]. A different form of cooling called Doppler cooling was proposed by D. J. Wineland and his group and T.W. Hansch, and his group around the same time in 1975 [12]. These two research groups demonstrated the technique in 1978 [10, 13]. Doppler cooling allowed the particles to reach a temperature called the Doppler temperature where the velocity centric distribution function width is comparable to the line-width of the atomic transition of the atom. This allowed the estimation of the Doppler temperature as $T_D = \hbar\Gamma/2\kappa_B$, where Γ is the line-width, κ_B is the Boltzmann constant. The trapping of ions was in many ways quite different compared to that for atoms. Motional state quantisation has to be taken into consideration when ions are to be considered. This resulted in absorption spectrum of the ions to contain sidebands. However, the Doppler temperature for the ions came out to be the same as that for atoms. Later, along with Doppler cooling, several other techniques of cooling emerged e.g. sympathetic cooling. In sympathetic cooling, the ions come in contact with atoms of another species. The species can be cooled more easily by the use of laser. D. J. For example, beryllium ions cooled by a laser were used to cool mercury ions in 1986 [14].

With time, several other techniques of cooling trapped species were experimentally tried, for instance, Sisyphus cooling [15], resolved sideband cooling [16], Raman sideband cooling [17], electromagnetically induced transparency cooling [18]. These techniques allowed for a significant reduction in particle energies and thereby increased the confinement times within the trap. This allowed the researchers to come up with many interesting applications in diverse fields of science and engineering. However, the ion traps using radio frequency electric fields were not the only traps used for trapping sub-atomic, meso-atomic particles.

Several other traps, e.g. Penning trap and Penning-Malmberg trap, were also invented and are used till date to trap neutral as well as charged species of particles. The particular choice of trap depends on the application for which it is needed. Though the Paul trap is able to provide a strong confinement, it suffers from the problem of micro motion. This causes RF heating which is a very well documented complex phenomena, but not clearly understood [19]. Another that

that hampers the device is that of the ambient magnetic fields. These fields can induce severe decoherence into the system if magnetic field independent optical transitions are not used [20]. In spite of these issues it is extensively used not only in mass spectroscopy [6] but also in areas such as quantum information processing [21], frequency standards of atomic clocks [22], quantum computation [23], and even life sciences for DNA sequencing [24].

Unlike the Paul trap which uses time-varying electric fields, the Penning trap uses a combination of static electric and magnetic field to confine particles. The geometry of both the traps is similar except that in Penning trap the particle has a stable axial motion but an unstable radial motion. The ion is therefore confined in the radial plane by applying a magnetic field along the axial direction. The resulting equation of motion gets coupled in x - y (radial) plane whereas the motion in z (axial) direction is independent. The magnetic field in these traps is usually provided by superconducting magnets. This allows for an effective shielding from the ambient field. The problem of decoherence observed in Paul trap is overcome as optical transitions are field independent. However, the trap experiences Zeeman splitting due to an external magnetic field. Nowadays, this issue has been overcome by using odd isotopes with hyperfine structures. One of the primary advantages of the Penning trap is its long coherence time. This trap is widely used testing fundamental physics e.g. test quantum electrodynamics (QED), CPT symmetry, determination of fundamental constants etc, [25].

Penning-Malmberg trap is a variation of Penning trap. The electric potentials in a Penning-Malmberg trap are not perfectly quadratic as in the case of Paul trap and Penning trap. The potentials in this trap configuration are produced by the application of DC voltages to a stack of hollow cylindrical electrodes [26]. The particles in this trap are subjected to the Lorentz force which deflects the particles perpendicular to the magnetic field causing them to spiral around the field. These particles accelerate and, therefore, radiate causing a self-cooling of the particles. ALPHA experiment uses this trap configuration to work with antimatter [27].

A conventional single frequency Paul trap has been successfully utilized in the confinement of charged particles with dimensions ranging from tiny ions to macro sized charged species like biomolecules and DNA sequences. A single frequency Paul trap has several applications in diverse fields as mentioned above. In a conventional single frequency Paul trap, it is possible to confine species that differ greatly with respect to their charge to mass ratio. But the weakly confined charge species is pushed away from the trap centre [28]. Hence, such simultaneous confinement is not very effective.

The recently introduced dual frequency Paul trap is able to trap species whose charge to mass ratio differs from each other significantly. This feature holds tremendous prospect in trapping antimatter such as anti hydrogen [29]. Production of anti hydrogen requires the ability to simultaneously trap antiprotons and positrons in a given space. Till recently, this was done using a Penning trap where a constant magnetic homogeneous magnetic field and an inhomogeneous static electric field allowed for the confinement of particles. The ALPHA experiment [30, 31] and ATRAP experiment [32, 33] rely on a variation of the Penning trap for their initial confinement.. However, it is not possible to trap particles of opposite charges on account of the static electric field. Recombination is achieved by ejecting antiprotons into the cloud of positrons but most of the antiprotons are lost during recombination.

For anti hydrogen formation, the problem of confinement of antiprotons and positrons can be very effectively handled by using a dual frequency Paul trap [29]. This trap design will allow us to combine the stability parameters of both particles and also ensure charge cloud of the two species to overlap inside the trap. Gas phase chemistry of ions at low temperatures can now be more effectively

probed using this newly conceptualised trap. Using a single frequency Paul trap only similar charge to mass ratio particles could be probed. In it, the lighter species usually was a charged ion co-trapped with a small molecule of a mass of a few hundred AMU's. A dual frequency trap will allow the scientists to expand the realm of working by including much heavier particles, for example graphene, DNA[34].

A dual frequency Paul trap will allow us to modify the stability regions, access new operating modes, and explore new ways to perform different kinds of analysis through more sophisticated trapping architectures. It is believed that the device holds great prospects in expanding the experimental framework in which ion clouds and crystals can be prepared and manipulated. This is likely to advance our efforts in the field of quantum information processing as well [35]. With such great prospects, the device is very likely to spur theoretical as well as experimental research. It would therefore be very interesting to explore the dynamics of charged particles in the newly conceptualised dual frequency Paul trap and see in what ways it is different from a single frequency Paul trap.

In an ideal Paul trap, whether single frequency or double frequency Paul trap, a quadrupole electric fields is produced field. In a practical Paul trap there will always be nonlinearity which may be cause due to the truncation of the electrodes [36], the apertures in the electrodes [36], machining imperfections [37]. These nonlinearities are more profound in other geometrical variants e.g., cylindrical [38, 39] and rectilinear ion traps [40]. Nonlinearity in the electric fields always play a role in affecting the performance of mass based spectrometers [41, 42], mass resolution [43, 44], and signal sensitivity [45]. There are ways to optimize the electric fields. For example, commercial Paul traps either increased the distances between the endcap electrodes or modify the hyperbolic angle [46]. For mass selective axial ejection, nonlinear fringing field has been used in linear ion trap [47, 48].

5. Justification of the study

As evident from the literature survey, the single particle dynamics has been extensively studied inside the single frequency Paul trap. Both ideal and practical traps with non linear components have been studied in depth and detail. The new trap, namely, dual frequency Paul trap has been studied for single particle dynamics in [34, 35]. In these works, an ideal trap has been considered and stability of the ions has been quantitatively derived. Since these traps have great prospects in trapping species with extremely different charge to mass ratios, they are likely to find application in generating and trapping antimatter such as anti-hydrogen. Any trap in practical setting shall require a thorough analysis of the various non linear affects that may emerge during the functioning of the trap. It still remains to be seen how these non linear affects will manifest themselves in the analysis of a dual frequency Paul trap.

6. Objective of the study

We will focus on understanding the dynamics of charged particles in a dual frequency Paul trap under non ideal scenarios for example, when stray electric fields or when the electric fields due to phase mismatch, space charge effect, deviation from a perfect quadrupole potential existing inside an ideal trap.

The study will focus on how the position x(t) of the particle evolve under the influence of additional electric fields. On account of a deviation from a perfect quadrupole potential, the secular frequency

of the particle motion will be affected and needs to be calculated. Secular frequency plays an important role in determining the dimension of potential well to ensure that the particle remains trapped inside the Paul trap.

7. Hypothesis

A dual frequency Paul trap will exhibit deviations from its ideal characteristics. The following are the proposed hypothesis:

• The ion will exhibit an enormous heating on account of the stray electric field and field due to a phase mismatch.

• The charged particles will exhibit non linear resonances.

• The ion motion is likely to have a natural frequency series along with some other non linear frequency series.

8. Research design

The design of the research problem will revolve around the solution (analytical approximate) of differential equations that underline the dynamics of the charged particles in the presence on nonlinear components inside the Paul trap.

The charged particle in an ideal dual frequency Paul trap is under the influence of a quadrupole potential given by

$$\emptyset(x,y,z,t) = \left(\frac{\mathrm{U} + V_1\cos(\omega_1 \mathrm{t}) + V_2\cos(\omega_2 \mathrm{t})}{r_o^2}\right)(x^2 + y^2 - 2z^2) \qquad (1)$$

Where U is the DC voltage and $V_{1,2}$ is the RF voltages with frequencies ω_1 and ω_2 respectively, applied to the electrodes of Paul trap. The trap dimension is given by r_0.

The electric field is given by the negative of the gradient of the potential, i.e.

$$\vec{E} = -\left(\frac{\partial \emptyset}{\partial x}\hat{\imath} + \frac{\partial \emptyset}{\partial y}\hat{\jmath} + \frac{\partial \emptyset}{\partial z}\hat{k}\right) \qquad (2)$$

To this field gets added a stray electric field and the field due to the phase mismatch. The combined electric field is therefore given by:

$$\vec{E}\,Total = \vec{E} + \vec{E}\,stray + \vec{E}\;phase \qquad (3)$$

The charged particle dynamics can then be formulated as:

$$m\frac{d^2\vec{r}}{dt^2} = q\,\vec{E}\,Total \qquad (4)$$

Where m is the mass of the charged particle and q is the charge of the particle.

In a dual frequency Paul trap, the added hexapole potential will result in a net potential given by:

$$\emptyset(x,y,z,t) = (\mathrm{U} + V_1\cos(\omega_1 t) + V_2\cos(\omega_2 t))\left(\frac{A_1}{r_o^2}\left[z^2 - \frac{r^2}{2}\right] + \frac{A_2}{r_o^3}\left[z^3 - \frac{3}{2}r^2 z\right]\right) \quad (5)$$

where $r^2 = x^2 + y^2$. The electric field is given by:

$$\vec{E} = -\nabla\emptyset \quad (6)$$

The dynamics of the charged particle can then be simply written as:

$$m\frac{d^2\vec{r}}{dt^2} = q\,\vec{E} \quad (7)$$

9. Research methodology

The research problem and the research design has been formulated after a thorough literature review. The problem formulated under Eq. 4 will be tackled by the Modified Lindstedt-Poincare (MLP) method [49, 50]. The analysis of the problem formulated in Eq. 7 will be handled using some well documented perturbation methods, for example, Poincare-Lighthill-Kuo method, amongst others [51, 52, 53].

10. Scheme of chapterisation

The chapters will be arranged as follows:
• Introduction
• Dynamics with stray electric field and electric field due to phase mismatch inside a dual frequency Paul trap.
• Dynamics of charged particle on account of deviation from an ideal quadrupole potential inside a dual frequency Paul trap.

11. Flow of work (academic year 2020-21)

a. July 2020 to December 2020

• Study the dynamics of charged particle in presence of field due to phase mismatch.
• Construct a distribution function for dynamics of charged particle under the influence of stray electric field.

b. January 2021 to July 2021

• Study the various perturbation methods that can be applied to the Paul trap problem of added hexapole and octupole fields.
• Solve of particle dynamics in presence of hexapole and octupole fields.

12.Bibliography

References

[1] W. Paul, “Electromagnetic traps for charged and neutral particles”, Rev. Mod. Phys., vol. 69, no. 3, pp. 531, Jul. 1990

[2] W. Paul and H. Steinwedel, “A new mass spectrometer without a magnetic field”, Z. Naturforsch., vol 8a, pp. 448, Jul. 1953

[3] W. Paul and H. Steinwedel, “Apparatus for separating charged particles of different specific charges”, U.S. Patent 2,939,952A, Jun. 1960

[4] R. E. March, R. J. Hughes and J. F. J. Todd, Quadrupole storage mass spectrometry, New York, USA, Wiley–Interscience, 1989

[5] R. E. March and J. F. J. Todd (Eds), Practical aspects of ion trap mass spectrometry, vols. 1, 2 and 3, CRC Press, Boca Raton, FL, USA, 1995

[6] G. Stanford Jr, “Ion trap mass spectrometry: a personal perspective”, Journal of the American Society for Mass Spectrometry, vol. 13, no. 6, pp. 589, Jun. 2002

[7] J. D. Prestage, Go. J. Dick, and L. Maleki, “New ion trap for frequency stan- dard applications”, Journal of Applied Physics, vol.66, no. 3, pp. 1013, Apr. 1989

[8] P. Wieburg, A Linear Paul Trap for Ytterbium Ions, Master Thesis, Universität Hamburg, pp.4, Apr. 2014

[9] H. Schaaf, U. Schmeling, and G. Werth, “Trapped ion density distribution in the presence of He-buffer gas”, Applied Physics, vol. 25, no. 3, pp. 249, Jul. 1981

[10] W. Neuhauser et al., “Localized visible Ba+ mono-ion oscillator”, Phys. Rev. A., vol. 22, no. 3, pp. 1137, Jul. 1980

[11] T. Sauteretal., “Quantum jumps observed in the fluorescence of a single ion”, Optics Communications, vol. 60, no. 5, pp. 287, Dec. 1986

[12] T. W. Hänsch and A. L Schawlow, “Cooling of gases by laser radiation”, Optics Communications, vol. 13, no. 1, pp. 68, Jan. 1975

[13] D. J. Wineland, R. E. Drullinger, and F. L. Walls, “Radiation-pressure cooling of bound resonant absorbers”, Phys. Rev. Lett., vol. 40, no. 25, pp. 1639, Jun. 1978

[14] D. J. Larson et al., “Sympathetic cooling of trapped ions: A laser-cooled two- species nonneutral ion plasma”, Phys. Rev. Lett., vol. 57, no. 1, pp. 70, Jul. 1986

[15] Y. Castin et al., “Two-dimensional Sisyphus cooling”, Phys. Rev. A., vol. 50, no. 6, pp. 5092, Dec. 1994

[16] C. Monroe et al., “Resolved-Sideband Raman Cooling of a Bound Atom to the 3D Zero-Point Energy”, Phys. Rev. Lett., vol. 75, no. 22 , pp. 4011, Nov. 1995

[17] V. Vuletic´, “Degenerate Raman Sideband Cooling of Trapped Cesium Atoms at Very High Atomic Densities”, Phys. Rev. Lett., vol. 81, no. 26, pp. 5768, Dec. 1998

[18] M. Bienert and G. Morigi, “Cavity cooling of a trapped atom using elec- tromagnetically induced transparency”, New Journal of Physics, vol. 14, pp. 023002, Feb. 2012

[19] Q. A. Turchette et al., “Heating of trapped ions from the quantum ground state”, Phys. Rev. A, vol. 61, no. 6, pp. 063418, Jun. 2000

[20] F. S. Kaler et al., “The coherence of qubits based on single Ca+ ions”, J. Phys. B: At. Mol. Opt. Phys, vol. 36, no. 3, pp. 623, Jan. 2003

[21] J. M. Amini et al., “Toward scalable ion traps for quantum information processing”, New Journal of Physics, vol. 12, pp. 033031, Mar. 2010 −18 certainty”, Phys. Rev. Lett., vol. 116, no. 6 , pp. 063001, Feb. 2016

[22] N. Huntemann et al., “Single-ion atomic clock with 3_106 systematic uncertainty”, Phys. Rev. Lett., vol. 116, no. 6 , pp. 063001, Feb. 2016

[23] T. P. Harty, “High-Fidelity Preparation, Gates, Memory, and Readout of a Trapped-Ion Quantum Bit”, Phys. Rev. Lett., vol. 113, no. 22 , pp. 220501, Nov. 2014

[24] S. Joseph et al., “Long DNA segment in a linear nanoscale Paul trap,” Nanotechnology, vol. 21, no. 1, pp. 015103, Nov. 2009

[25] K. Blauma, Yu. N. Novikovband and G. Werthc, “Penning traps as a versatile tool for precise experiments in fundamental physics”, Contemporary Physics, vol. 51, no. 2, pp. 149, Mar. 2010

[26] M. Charlton, “Antihydrogen for precision tests in physics”, Contemporary physics, vol. 49 . no. 1, pp. 29, Jun. 2008

[27] M. Ahmadi et al., “Observation of the 1S–2S transition in trapped antihydrogen”, Nature, vol. 541, no. 7638, pp. 506, Dec. 2016

[28] D. Offenberg et al., “Translational cooling and storage of protonated proteins in an ion trap at subkelvin temperatures”, Phys. Rev. A., vol. 78, no. 6, pp. 0061401(R), Dec. 2008

[29] N. Leefer et al., “Investigation of two-frequency Paul traps for antihydrogen production”, Hyperfine Interactions, vol. 238, pp. 12, Nov. 2017

[30] G. B. Andresen et al., “Trapped Antihydrogen”, Nature, vol. 468, no. 7324, pp. 673, Dec. 2010

[31] G. B. Andresen et al., “Confinement of antihydrogen for 1,000 seconds”, Nature Phys., vol. 7, no 7, pp. 558, Jul. 2011

[32] C. H. Storry et al., “First laser-controlled anti-hydrogen production”, Phys.Rev. Lett, vol. 93, no. 26, pp. 263401, Dec. 2004

[33] G. Gabrielse, “Trapped antihydrogen in its ground state”, Phys. Rev. Lett, vol. 108, no. 11, pp. 113002 , Mar. 2012

[34] D. Trypogeorgos and C. J. Foot, “Co-trapping different species in ion traps using multiple radio frequencies”, Phys. Rev. A., vol. 94, no. 2, pp. 023609, Aug. 2016

[35] G. C. Possa and L. F. Roncaratti, “Stability diagrams for Paul ion traps driven by two frequencies”, J. Phys. Chem. A, vol. 120, no. 27, pp. 4915, Feb. 2016

[36] E. C. Beaty, “Calculated electrostatic properties of ion traps”, Phys. Rev. A, vol. 33, pp. 3645–3656, 1986

[37] W. Xu, W. J. Chappell, R. G. Cooks, Z. Ouyang, “Characterization of electrode surface roughness and its impact on ion trap mass analysis”, J. Mass Spectrum. vol. pp. 44, 353–360, 2009

[38] J. M. Wells, E. R. Badman, R. G. Cooks, “A quadrupole ion trap with cylindrical geometry operated in the mass-selective instability mode”, Anal. Chem. vol. 70, pp. 438–444, 1998

[39] G. X. Wu, R. G. Cooks, Z. Ouyang, “Geometry optimization for the cylindrical ion trap: Field calculations, simulations, and experiments”, Int. J. Mass Spectrum, vol. 241, pp. 119–132, 2005

[40] Z. Ouyang, G. X. Wu, Y. S. Song, H. Y. Li, W. R. Plass, R. G. Cooks, “Rectilinear ion trap: Concepts, calculations, and analytical performance of a new mass analyzer”, Anal. Chem. 76, 4595–4605, 2004

[41] J. M. Wells, W. R. Plass, G. E. Pattison, Z. Ouyang, E. R. Badman, R. G. Cooks, “ Chemical mass shifts in ion trap mass spectrometry: Experiments and simulations”, Anal. Chem., vol. 71, pp.3405–3415, 1999

[42] H. Y. Li, W. R. Plass, G. E. Pattison, R. G. Cooks, “Chemical mass shifts in resonance ejection experiments in the quadrupole ion trap. J. Mass Spectrum”, vol. 37, pp. 1051–1058, 2002

[43] J. Franzen, “The non-linear ion trap. Part 4. Mass selective instability scan with multipole superposition”, Int. J. Mass Spectrom. Ion Process, vol. 125, pp. 165–170, 1993

[44] P. H. Dawson, N. R. Whetten, “Non-linear resonances in quadrupole mass spectrometers due to imperfect fields. I. The quadrupole ion trap”, Int. J. Mass Spectrom. Ion Phys, vol. 2, pp. 45–59 1969

[45] D. M. Eades, J. V. Johnson, R. A. Yost, “Nonlinear resonance effects during ion storage in a quadrupole ion trap”, J. Am. Soc. Mass Spectrum, vol. 4, pp. 917–929, 1993

[46] R. E. March, J. F. J Todd, “Practical Aspects of Ion Trap Mass Spectrometry”, vol 1, chap. 3, Fundamentals of Ion Trap Mass Spectrometry. CRC Press, New York, 1995

[47] F. A. Londry, J.W. Hager, “Mass selective axial ion ejection from a linear quadrupole ion trap”, J. Am. Soc. Mass Spectrom, vol. 14, pp. 1130–1147, 2003

[48] M. Gunna, T. A. Biesenthal, “Performance enhancements of mass selective axial ejection from a linear ion trap”, J. Am. Soc. Mass Spectrom, vol. 20, pp. 1132–1140, 2009

[49] P. Amore and A. Aranda, “Presenting a new method for the solution of nonlinear problems”, Phys. Lett. A, vol. 316, pp. 218, Sep. 2003

[50] V. Saxena and K. Shah, “ Plasma dynamics in dual frequency Paul trap using Tsallis distribution”, IEEE Transactions on Plasma Science, vol. 46, no. 3, pp. 474-481, March 2018

[51] H. S. Tsien, “The Poincare-Lighthill-Kuo method”, Adv. Appl. Math, vol. 4, pp. 281–349, 1956

[52] X.Y. Zhou, Z. Q. Zhu, C. Q. Xiong, R. Chen, W. J. Xu, H. X. Qiao, W. P. Peng, Z. X. Nie, Y. Chen, “Characteristics of stability boundary and frequency in nonlinear ion trap mass spectrometer”, J. Am. Soc. Mass Spectrum”, vol. 21, pp. 1588–1595, 2010

[53] X. Y. Zhou, C. Q. Xion, Xu, G. P. Xu, H. Liu, Y. Tang, Z. Q. Zhu, R. Chen, H. X. Qiao, Y. H. Tzeng, W. P. Peng, Z. X. Nie, Y. Chen, “Potential distribution and transmission characteristics in a curved quadrupole ion guide”, J. Am. Soc. Mass Spectrum, vol. 22, pp. 386–398, 2011

MANAV RACHNA
(Established under Haryana Act No. 26 of 2014)

Swami Vivekananda Library and Resource Centre
Manav Rachna University

SIMILARITY VERIFICATION CERTIFICATE

Title: Effects of non-linearities in a dual frequency Paul trap

Researcher: Amiranjan Kansal Registration Number: 2K20PFE007

Supervisor: Dr. Charu Pathak Department: Electronics & Communication Engineering

This is to certify that the above mentioned Short Synopsis/Thesis was scanned for similarity index through Turnitin Software on 22/3/2021 with submission ID 1539192873 and the similarity index was found to be 9 %. The complete report running into 11 Pages, 4304 Word count with File Size 2103 KB is being forwarded to the Research Supervisor/DRC/DRB for review.

Date: 19/7/2021

Swami Vivekananda Library and Resource Centre Faridabad ★ Manav Rachna University ★
19/7/2021

The complete report of the above Short Synopsis/Thesis has been reviewed and the similarity index is below the accepted norms as per the University Grants Commission (Promotion of Academic Integrity and Prevention of Plagiarism in Higher Educational Institutions) Regulations 2018. The Short Synopsis/Thesis may be considered for further processing

Akansal 19/7/2021
Research Scholar

Charu Pathak 19/7/2021
Research Supervisor

Short Synopsis Anuranjan Kansal 22.03.2021

by Anuranjan 1 Kansal

Submission date: 22-Mar-2021 01:41AM (UTC-0700)
Submission ID: 1539192873
File name: Anuranjan_Kansal.doc (197.5K)
Word count: 4304
Character count: 21832

Effects of non-linearities in a dual frequency Paul trap

SHORT SYNOPSIS

by

Anuranjan Kansal
Registration number: 2K20-PFE-007

Dr. Charu Pathak (Supervisor)
Associate Professor

Dr. Varun Saxena (Co-Supervisor)
Assistant Professor

2019-2020

1. Abstract

A analysis of dynamics of charged particles inside a dual frequency Paul trap in presence of non idealities is being studied. The trap may develop a phase mismatch between the electrodes where the RF voltage is applied. Moreover, an ideal trap assumes an ideal quadrupole potential. In reality, hexapole and octupole potentials develop inside the Paul trap. The non linear affects become dominant and modify the secular frequency inside the trap. In this study, we attempt to find the deviation in secular frequency that is likely to develop on account of hexapole and octupole fields.

2. Review of literature

The science of ion confinement evolved from molecular beam physics and spectroscopy. In 1953, W.Paul and H. Steinwedel introduced the concept of mass analysis of charged particles by trapping ions. They proposed the concept of what has been described by W. Paul in his Noble lecture in 1989 as quadruple mass filter [1, 2]. This mass filter comprised of four hyperbolically shaped electrodes. Periodically varying potentials were applied to electrode pairs which were placed along two given axis. Due to the periodically varying sign of the electric force developed between the pair of electrodes it was possible to achieve focussing and defocusing in both the direction where the electrode pairs were located alternating in time. Hence it was possible for the particles to traverse in the third direction longitudinally without hitting the electrodes. The concept of dynamic stabilization in two dimensions was extended to three dimensions to achieve what came to be known as an ion trap. This trap configuration

Short Synopsis Anuranjan Kansal 22.03.2021

ORIGINALITY REPORT

Excluding matches less than 14 words

9%	4%	10%	0%
SIMILARITY INDEX	INTERNET SOURCES	PUBLICATIONS	STUDENT PAPERS

PRIMARY SOURCES

1	Xiaoyu Zhou, Caiqiao Xiong, Shuo Zhang, Ning Zhang, Zongxiu Nie. "Study of Nonlinear Resonance Effect in Paul Trap", Journal of The American Society for Mass Spectrometry, 2013 Publication	2%
2	Nathan Leefer, Kai Krimmel, William Bertsche, Dmitry Budker, Joel Fajans, Ron Folman, Hartmut Häffner, Ferdinand Schmidt-Kaler. "Investigation of two-frequency Paul traps for antihydrogen production", Hyperfine Interactions, 2016 Publication	2%
3	Varun Saxena, Kushal Shah. "Plasma Dynamics in a Dual-Frequency Paul Trap Using Tsallis Distribution", IEEE Transactions on Plasma Science, 2018 Publication	1%
4	Stafford, G.. "Ion trap mass spectrometry: a personal perspective", Journal of the American Society for Mass Spectrometry, 200206 Publication	1%

5	docplayer.net Internet Source	1%
6	epdf.tips Internet Source	1%
7	hdl.handle.net Internet Source	1%
8	Varun Saxena. "Collective Dynamics Inside Paul Trap With Stray Electric Field Using Nonextensive Distribution Function", IEEE Transactions on Plasma Science, 2020 Publication	1%
9	Günter Werth, Sven Sturm, Klaus Blaum. "Zeeman Spectroscopy in Penning Traps", Elsevier BV, 2018 Publication	1%
10	etheses.dur.ac.uk Internet Source	1%

Exclude quotes	Off	Exclude matches	Off
Exclude bibliography	Off		